

Non-baryonic Dark Matter Searches

Y. Ramachers

*University of Oxford, Department of Physics,
Nuclear and Particle Physics Lab., 1 Keble Road,
Oxford OX1 3RH, U.K.*

*present address: LNGS, INFN, 67010 Assergi, Italy
E-mail:yorck.ramachers@lngs.infn.it*

Abstract

The emphasise in this review about non-baryonic dark matter will be on experimental approaches to this fast evolving field of astroparticle physics, especially the direct detection method. The current status of experimental techniques will be reviewed and recent highlights as well as future plans will be introduced.

1 Introduction

The concept of dark matter in the universe is by now well established (see [1] for a collection of recent reviews) but poses still a remarkable problem thereby inspiring the creativity of astronomers and physicists. Nowadays there exist two separate dark matter problems, the baryonic and the non-baryonic dark matter problem (including a non-zero vacuum energy). That separation is nicely visualised in [2] from which Fig. 1 has been taken. The separation is founded on the well established constraints on the allowed amount of baryonic matter in the universe from primordial nucleosynthesis (see [3] and references therein). Every hint from measurements, typically on large astronomical scales, for a mass abundance above the allowed one is actually an evidence for non-baryonic dark matter.

As more refined measurements from experimental cosmology are collected, like from distant supernova Ia searches, large scale flows or cosmic microwave background [4], the question of existence of dark matter shifts rather to the question of abundance and nature of dark matter, especially for its non-baryonic part. That part in particular is one point where particle physics and astrophysics merged to form the field of astroparticle physics. Plenty of candidates for non-baryonic dark matter have been proposed. Here it should be noted that the accumulating evidences for the existence of a finite vacuum energy, like a cosmological constant, do not render a non-baryonic matter contribution unnecessary. In fact, the numerous candidates which are classified as cold dark matter (non-relativistic thermal or non-thermal relics from the early universe) are still necessary ingredients for structure formation in the universe [4].

The favourite particle candidates for non-baryonic dark matter in terms of experiments aiming at their detection are the axion and the neutralino. Since there exist extensive reviews about particle candidates and in particular about the axion and the neutralino, an introduction of these main candidates is considered to be beyond the scope of this review (see e.g. [5]). They can also be classified as WIMPs (weakly interacting massive particles) together with less prominent candidates (axinos, gravitinos, etc.). In fact, from the experimental point of view the term WIMP summarises almost all necessary requirements for a dark matter particle candidate. Any neutral, massive (between a few GeV and a few hundred TeV for thermal relics) and weakly interacting particle can represent a good candidate. Experiments aiming at the detection of particles with properties as above are described below ¹ (compare also the recent review [7]).

2 Detection concepts

The experiments to reveal the nature and abundance of particle dark matter can be divided in two conceptually different approaches, direct and indirect detection. The physics underlying the direct detection technique is the elastic scattering of a WIMP with a nucleus of the detector. Therefore, the main observable is the deposited energy by the recoiling nucleus. For indirect detection the WIMPs first have to be accumulated in a gravitational potential to increase their density and therefore their annihilation rate. The annihilation products, high energy neutrinos, are then detected via their conversion to muons. Hence the signatures are muons originating from the centre of the earth or the sun, so called upward-going muons from these well defined sources.

Additional observables for the direct detection technique which can serve to increase the signal to noise ratio are either recoil-specific or WIMP-specific. The recoil-specific observables are e.g. pulse-shapes or the partitioning of energy release into ionization and phonon signals or scintillation and phonon signals (see Fig. 2 for a summary of applied techniques to reduce background).

WIMP-specific observables result from the assumption of the existence of a WIMP halo around our galaxy as motivated from galaxy rotation curves [8]. Such a halo would yield kinematic signatures for WIMP-detection. The movement of the sun through the halo (excluding a conspiracy of a co-rotating halo) induces an annual modulation of WIMP-rates in the detector because the earth velocity would add to the mean kinetic energy of WIMPs impinging on the detector in summer and subtract in winter [9]. The asymmetry of the WIMP-wind itself would also induce a diurnal modulation for a recoil-direction sensitive detector [10].

In order to rank the various background suppression mechanisms for direct detection one has to keep in mind that the powerful background discrimination via recoil-specific observables (factors of 100 and more have been reported, see e.g. [11, 12]) is systematically limited by neutron elastic scattering processes

¹That excludes the specialised experiments aiming at the detection of axions. For a collection of recent references on this topic, see [6].

since these also produce nuclear recoils. The WIMP-specific observables are limited as well. First of all, the distribution function of WIMPs in the halo, see below, is unknown. Second, the annual modulation effect is small, of the order of a few percent. A recoil-direction sensitive detector would exploit the much larger diurnal modulations of the order of tens of percent modulations but detecting the tiny tracks from nuclear recoils is a formidable experimental task, see the DRIFT proposal below.

A comparison of indirect and direct detection methods has been worked out either model-independent or for a specific candidate particle [13, 14, 15]. A general feature of such a comparison is that indirect searches are more sensitive for large WIMP-masses and spin-dependent interactions (see below) than direct searches (see also [16]). Therefore these two approaches are complementary. Additionally, in case both techniques would give a consistent signal it would be possible to obtain in principle not only the approximate mass and elastic scattering cross section but also the annihilation cross section [17]. For more details about the indirect detection method, I refer to [16] and references therein. Note that in case of the neutralino as the dark matter particle candidate another complementarity between direct detection and accelerator experiments has been shown [18] (for a discussion, see [19]).

Now for the direct detection technique, it is worth summarising the main experimental requirements.

- Energy threshold: As low as possible due to the quasi-exponentially decreasing signal shape as function of recoil energy. The relevant energy region is generally below 100 keV.
- Target mass: As high as possible due to the low cross section for WIMP-nucleus elastic scattering. Direct WIMP detection means rare event search, i.e. the already tested rates are of the order of one count/(day kg keV).
- Background: As low as possible, especially the omnipresent neutron flux due to the production of nuclear recoils, simulating WIMP events.

The exact dependencies of the direct detection technique on physical parameters can be extracted from eq.1:

$$\frac{dR}{dQ} = N_T \frac{\rho_0 \sigma_0}{2 m_W \mu^2} F^2(Q) \int_{v_{\min}}^{v_{\max}} \frac{f(v)}{v} dv \quad ; \quad v_{\min} = \sqrt{\frac{E_{thr} m_N}{2 \mu^2}} \quad (1)$$

where dR/dQ is the measured quantity, the energy spectrum in rates over unit energy and unit detector mass. The other parameters can be classified as either completely unknown, like properties of the unknown WIMP, mass m_W and elastic scattering cross section σ_0 , or estimated input from astrophysics, like the local halo density ρ_0 (0.3-0.7 GeV/cc), escape velocity v_{\max} (≈ 600 km/s) from the galactic potential and the WIMP-halo distribution function $f(v)$, often approximated by a Maxwellian distribution (see [20] and references therein). The last set of values represents the number of targets N_T , target nucleus mass m_N , reduced mass $\mu = (m_W m_N)/(m_W + m_N)$ and detector threshold E_{thr} . The

form factor $F^2(Q)$ parametrises the loss of coherence for the WIMP-nucleus interaction as the WIMP-energy increases. It represents an input from nuclear physics and depends on the type of WIMP interaction considered, since the elastic scattering cross section has two distinct interaction channels, a scalar or spin-independent and an axial or spin-dependent channel (for details, see [5] and the discussion in [20]). Hence, depending on the spin-properties of the target nuclei, the appropriate form factor has to be used.

3 Current Experiments

The direct detection of WIMPs became a very dynamic field of research during the last years. There are about 20 experiments running or being prepared worldwide and even more planned for the near future (for collections of contributions from most of these, see [21, 22]). Various techniques and detector systems are applied. They can be classified by the applied detectors [7]. Here they are classified by their ability to discriminate nuclear recoils to some extent, i.e. to use recoil-specific observables (compare Fig. 2). That separation of experiments might give the impression that the most advanced experiments will use recoil discrimination techniques. On the other hand, note that this particular ability also adds complexity and therefore there are in fact experiments which do not apply any recoil discrimination but, nevertheless, give competitive perspectives (see below).

As shown in Fig. 2, the trick is for all no-discrimination detectors, like germanium semiconductor detectors (HD-Moscow [23], HDMS [23], GENIUS [24]), the cryogenic bolometers (CUORE [25], Tokyo [26], CRESST [12], Rosebud [27]), the superheated superconducting grains detector (ORPHEUS [28]) or the NaI scintillator ELEGANT V [29], to use materials and shieldings for the setup as radio-pure as possible. Since by now this kind of experiments have already collected a large amount of experience in using clean materials it has been thought that their sensitivity might have reached a saturation and no further breakthroughs could be expected. As it turned out, this assumption is not true at least for germanium detectors (see the GENIUS expectation in the next section).

The lowest background and therefore the best limit from raw data is still obtained by the Heidelberg–Moscow experiment. It uses an enriched ^{76}Ge detector of 2.758 kg active mass and reached a background near threshold of $5.7 \cdot 10^{-2}$ counts/(day kg keV). Due to the rather high threshold of 9 keV its limit for lower WIMP-masses can be combined with another germanium experiment [30] to give a combined Ge-diode limit (see Fig. 5) close to the currently best limits on spin-independent WIMP–nucleon interactions. HDMS is a specialised WIMP-detection setup from the same collaboration using a germanium well-type detector as active veto for a small inner germanium detector. After exchanging the inner natural germanium crystal by a ^{73}Ge enriched crystal the prospects are to improve the existing limit by about a factor of 5-10, thereby challenging current limits.

Other more complex techniques used for raw data experiments are cryogenic

detectors. Two collaborations published first results recently, the LiF-crystal experiment in Tokyo [26] and Rosebud [27] using sapphire (Al_2O_3) crystals. While the sapphire setup does not give competitive results so far it gives important insight into background contributions for cryogenic experiments in general. The LiF-experiment, although operating still at a shallow depth (15 m.w.e.), now improved the limit for light WIMP masses below 5 GeV (see Fig. 3). Due to their target materials both experiments are most sensitive for light WIMPs and the spin-dependent interaction channel. The Tokyo experiment will soon move to a deep underground laboratory and tries to remove identified background sources close to the detectors so that their estimate is to improve the current limit by an order of magnitude. Similar considerations have been put forward for Rosebud.

The pulse-shape discrimination technique for NaI-scintillator detectors (DAMA [31], UKDMC [32]) has been the first applied discrimination technique and turned out to be quite effective for increasing energies. Still the best limit on WIMP–nucleon cross sections come from the DAMA collaboration (for the scalar channel above 40 GeV, compare Fig. 5). The calibration of this method by the production of nuclear recoils from neutrons showed that these pulses are significantly faster than electron recoil pulses from photons or electrons. Recently, there emerged the feature of a class of pulses even faster than nuclear recoil pulses in two different experiments using NaI detectors (UKDMC and Modane [33]). These are considered to belong to an unknown background source and might even give a systematic limit of sensitivity for this technique. However, this effect is still under investigation and might as well be removed in the near future.

A highlight of NaI detectors is not only their discrimination ability and thereby the high sensitivity for WIMP detection but also the possibility to setup high target masses like the DAMA-experiment (87.3 kg active volume, see Fig. 4). This puts the DAMA-experiment into the unique position of having the ability to even use WIMP-specific observables like the WIMP-signature of an annual modulation. Since that effect is just of the order of a few percent one has to collect a sufficient statistic to filter out the tiny modulation [34]. In fact, this collaboration announced an evidence for the detection of that WIMP-signature. As shown in Fig. 4, they see an annual modulation in their data consistent with the expectation for a WIMP at

$$m_W = 59_{-14}^{+17} \text{ GeV} \quad ; \quad \xi \sigma_{\text{scalar}}^{\text{nucleon}} = 7.0_{-1.2}^{+0.4} 10^{-6} \text{ pb},$$

where $\xi \sigma_{\text{scalar}}^{\text{nucleon}}$ is the local halo density normalised (to 0.3 GeV/cc) WIMP–nucleon scalar cross section. The consistency requirements are the proper kinematic modulation (phase, amplitude and period), single hits in detectors and the proper signal shape (maximum signal in the lowest energy bin and subsequent decrease). However, the excitement about this evidence is accompanied by a similarly engaged criticism [35] inside the dark matter community. Fortunately, this is a matter of experiment, i.e. it will be possible already in the near future to test the evidence by experiments rather than arguments.

The first competitors of the DAMA experiment which are expected to be able to test their result in the near future are the cryogenic detector experiments

CDMS and EDELWEISS [37]. They use a combined signal readout of phonon signals and ionization signals from germanium (and silicon in case of CDMS) crystals. The clue of this kind of readout scheme is that in germanium crystals the ionization efficiency of nuclear recoils is just about 25% (energy dependent, see [38] and references therein) compared to an electron recoil event. So far, they both suffered from the effect of incomplete charge collection of surface electron events which could mimic nuclear recoil events. Recently the CDMS experiment got rid of this problem (see Fig. 5 and [36]) and now they already test the DAMA result below about $m_W = 40$ GeV. The EDELWEISS collaboration is expected to follow that development soon and release a new improved limit comparable to or even better than the CDMS result.

Apart from that actual status report it is worth mentioning rather mid-term projects which show the variety of applied detection techniques in order to reduce background. The CASPAR proposal [39] uses small grains of CaF_2 scintillators (of the order of a few hundred nanometer diameter) dissolved in an organic scintillator. Calcium or fluorine nuclear recoils would only produce a scintillation signal from their grain whereas electron recoils would have a much larger range and would give signals from the organic scintillator as well which then could be discriminated. Another discriminating detector concept using ionisation and scintillation signal readout from liquid Xenon (or two-phase Xenon, gas and liquid), the ZEPLIN [40] project, is still in its R&D-phase but first tests are very promising.

The superheated droplet detectors PICASSO [41] and SIMPLE [42] also use the specific energy loss of nuclear recoils to discriminate against minimum ionising particles. They use a well known technique for neutron dosimetry, namely droplets of a slightly superheated refrigerant liquid embedded in a gel. The droplets would then act like tiny bubble chambers, exploding due to a nuclear recoil event. By tuning the relevant parameters, pressure and temperature, the bubbles can be made insensitive to nuclear radiation so that practically only recoils from fission processes and neutrons remain background sources. Both experiments are currently build up and first results from PICASSO and SIMPLE have been reported recently.

4 Future Plans

Although research in the field of direct detection evolves rapidly and more exciting results can be expected for the near future as mentioned above, there are three proposed detection concepts which shall be reported separately in order to point out their exceptional prospects ².

The DRIFT experiment (see Fig. 6) [43] represents the only test-phase operating recoil-direction sensitive experiment. It consists of a low-pressure TPC using 20 torr Xe- CS_2 (50:50) gas mixture. The crucial point for such a device is that it must be able to detect reliably the tiny tracks from nuclear recoils, i.e. the design goal is to achieve a less than 1 mm track resolution. In order to setup higher target masses despite the low-pressure gas, the idea is to abandon the

²Admittedly, due to personal preferences.

magnetic field. That would in principle worsen the track resolution due to enhanced diffusion. Therefore the detection concept has been changed in the sense that the TPC does not detect the drifted electrons but rather negative CS_2^- ions with considerably reduced diffusion. The prospects for this setup are very encouraging due to the ability to measure the most decisive WIMP-signature, the diurnal modulation due to the WIMP-wind. The plan is to operate a 20 m^3 TPC by the end of 2001.

The GENIUS proposal [24] is exceptional in the sense that it is a detection concept which works without specialised background discrimination procedures, i.e. it will not use nuclear recoil specific observables. This traditional detection method, using germanium semiconductor detectors, relies therefore on the utilisation of extreme radio-pure materials around the detectors. The idea is to remove all materials close to the crystals which were so far necessary to cool the detectors and instead operate them directly in liquid nitrogen which has been measured to be a very pure environment. The necessity to use that liquid nitrogen as shielding material scales the setup to a rather large size (dewar of 12 m diameter and height). On the other hand, that also admits to operate a large target mass (100 kg of natural germanium is planned for the first stage) in a common environment. The technical studies of operating 'naked' germanium crystals in liquid nitrogen have already been performed successfully. An estimation of the expected sensitivity, i.e. the background expected, can be seen in Fig. 7. Most dangerous appears the cosmic activation of the crystals while produced and transported on the earth surface due to spallation reactions with cosmic rays (hadronic component). The cited background expectation of $3.1 \cdot 10^{-2} \text{ counts}/(\text{y kg keV})$ below 100 keV would result in a WIMP-sensitivity more than 3 orders of magnitude below current best limits which definitely is an encouraging prospect.

The CRESST phase II concept [12, 44] consists of a combined signal readout from a scintillating crystal cooled to 12 mK. The light and phonon readout yields a very efficient discrimination mechanism as can be seen in Fig. 8. Test measurements using a non-optimised setup in a surface laboratory already give background suppression factors comparable to the ionization-phonon readout schemes seemingly without the problem of surface effects. Several scintillating crystals have been tested (BaF_2 , BGO, PbWO_4 and CaWO_4) and their light yields at cryogenic temperatures measured. The operation of the scintillator as a cryogenic calorimeter poses special problems for the light detection since no light guide touching the crystal surface (matching refractive indices) is allowed since that would distort the phonon signal. For light detection a second calorimeter, a thin sapphire crystal coated with silicon to improve light absorption, is placed next to one surface of the scintillator and the other surfaces are surrounded by mirrors (compare Fig. 8) ³. Apart from the discrimination abilities of the detector concept there is an additional advantage. Several target materials or scintillators can be used in such kind of setup which would result in an unique handle not only on the discrimination of the ambient neutron background, so far

³New measurements use diffuse Teflon reflectors instead, resulting in a factor two per unit area more efficient light yield [44].

considered to be the ultimate limiting factor, but also on the extraction of the WIMP signal due to its target mass dependence (see eq.1). Moreover, already in the existing cryogenic setup inside the Gran Sasso underground laboratory there is enough space to house some tens of kilograms of active mass, rendering a modulation signature search possible. A first scintillation detector made from CaWO_4 is expected to be mounted underground already at the beginning of 2000.

5 Conclusion

Non-baryonic dark matter is by now a well motivated concept from astronomy in the framework of a universe model containing cold dark matter. Several independent measurements from experimental cosmology indicate the necessity of a matter content above the allowed baryonic matter from primordial nucleosynthesis. In addition, particle physics offers attractive candidates for cold dark matter classified as WIMPs and initially motivated independent from cosmological reasoning (especially the neutralino as necessary ingredient of supersymmetric theories).

WIMP searches in the form of direct and indirect detection experiments are a very active field of research also because of the attractive interdisciplinarity between astro- particle- and nuclear physics. A large variety of direct detection experiments, on which this review focused, currently produce results or will start in the near future. In addition, the first WIMP-detection evidence has been announced and will soon be tested by independent experiments. The benefit from this kind of research is twofold and worth to be reminded. One would learn about the supposed major part of matter in the universe and about beyond standard model physics by detection of non-baryonic dark matter.

Acknowledgement

The author thanks the following researchers for providing informations about their experiments and valuable comments: R. Bernabei, G. Chardin, D.B. Cline, J. Collar, S. Cooper, H. Ejiri, M. Di Marco, J. Hellmig, H.V. Klapdor-Kleingrothaus, M. Lehner, L. Lessard, M. Minowa, K. Pretzl, B. Sadoulet, W. Seidel, N. Smith, N.J.C. Spooner, D. Tovey and HanGuo Wang.

References

- [1] M.S. Turner, *Rev. Mod. Phys.* **71**, S145 (1999); astro-ph/9901168; astro-ph/9904051; M. Rowan-Robinson, astro-ph/9906277; J. Silk, astro-ph/9903402
- [2] S. Dodelson, E. Gates and M. Turner, *Science* **274** 69 (1996)
- [3] K. A. Olive, astro-ph/9901231

- [4] N.A. Bahcall, J.P. Ostriker, S. Perlmutter and P.J. Steinhardt, *Science* **284**, 1481 (1999); astro-ph/9906463; S. Perlmutter, M.S. Turner and M. White, *Phys. Rev. Lett.* **83**, 670 (1999)
- [5] G. Jungman, M. Kamionkowski and K. Griest, *Phys. Rep.* **267**, 195 (1996); L. Roszkowski, hep-ph/9903467; J. Ellis, astro-ph/9812211; A. Bottino and N. Fornengo, hep-ph/9904469; A.D. Dolgov, astro-ph/9910532
- [6] G. Raffelt, *Nucl. Phys. Proc. Suppl.* **77**, 456 (1999); A. Kitagawa et al., hep-ph/9908445; S. Cebrian et al., *Astropart. Phys.* **10**, 397 (1999)
- [7] A. Morales, astro-ph/9810341
- [8] C. Firmani and V. Avila-Reese, in [22] p.367; A. Burkert and J.Silk, in [22] p.375; B. Fuchs, in [22] p.387
- [9] A. Drukier, K. Freese and D.N. Spergel, *Phys. Rev. D* **33**, 3495 (1986); K. Freese, J. Frieman and A. Gould, *Phys. Rev. D* **37**, 3388 (1988)
- [10] D.N. Spergel, *Phys. Rev. D* **37**, 1353 (1988)
- [11] CDMS coll., *Nucl. Phys. Proc. Suppl.* **70**, 64 (1999)
- [12] CRESST coll., *Astropart. Phys.* **12**, 107 (1999); P. Meunier et al., physics/9906017
- [13] J. Rich and C. Tao, Preprint *DAPNIA-SPP-95-01* (1995)
- [14] F. Halzen, astro-ph/9506304
- [15] M. Kamionkowski, K. Griest, G. Jungman and B. Sadoulet, *Phys. Rev. Lett.* **74**, 5174 (1995)
- [16] L. Bergström, astro-ph/9902172
- [17] J. Rich, *Astropart. Phys.* **4**, 387 (1996)
- [18] H. Baer and M. Brhlik, *Phys. Rev. D* **57**, 567 (1998)
- [19] H.V. Klapdor-Kleingrothaus and Y. Ramachers, *Eur. Phys. J. A* **3**, 85 (1998)
- [20] J.D. Lewin and P.F. Smith, *Astropart. Phys.* **6**, 87 (1996)
- [21] N.J.C. Spooner and V. Kudryavtsev, eds., *The identification of dark matter* (World Scientific, Singapore, 1999)
- [22] H.V. Klapdor-Kleingrothaus and L. Baudis, eds., *Dark Matter in Astrophysics and Particle Physics* (IOP Publ., Bristol, 1999)
- [23] L. Baudis et al., *Phys. Rev. D* **59**, 022001 (1999)
- [24] L. Baudis et al., *Nucl. Instrum. Methods A* **426**, 425 (1999); hep-ph/9910205

- [25] A. Alessandrello et al., in [22] p.785
- [26] W. Ootani et al., *Phys. Lett. B* **461**, 371 (1999)
- [27] S. Cebrian et al., *Astropart. Phys.* **10**, 361 (1999)
- [28] S. Casalbuoni et al., in [21] p.377
- [29] H. Ejiri et al., in [21] p.323
- [30] D. Abriola et al., *Astropart. Phys.* **10**, 133 (1999)
- [31] R. Bernabei et al., *Phys. Lett. B* **424**, 195 (1998); CERN Courier **39**, No.5, p.17 (1999); hep-ph/9903501
- [32] P.F. Smith et al., *Phys. Lett. B* **379**, 299 (1996); V.A. Kudryavtsev et al., *Phys. Lett. B* **452**, 167 (1999)
- [33] G. Gerbier et al., *Astropart. Phys.* **11**, 287 (1999)
- [34] Y. Ramachers, M. Hirsch and H.V. Klapdor-Kleingrothaus, *Eur. Phys. J. A* **3**, 93 (1998); F. Hasenbalg, *Astropart. Phys.* **9**, 339 (1998)
- [35] G. Gerbier et al., astro-ph/9710181; astro-ph/9902194
- [36] R. Gaitskell, Talk at TAUP99, Paris, France (1999)
- [37] L. Berge et al., *Nucl. Phys. Proc. Suppl.* **70**, 69 (1999); astro-ph/9801199
- [38] L. Baudis et al., *Nucl. Instrum. Methods A* **418**, 348 (1998)
- [39] N.J.C. Spooner et al., *Astropart. Phys.* **8**, 13 (1997)
- [40] N.J.T. Smith et al., in [21] p.335
- [41] R. Gornea et al., in [22], p.772
- [42] J. Collar et al., in [21], p.383
- [43] C.J. Martoff, in [21] p.389; D.P. Snowden-Ifft, in [21] p.395; M.J. Lehner, in [22] p.767
- [44] M. Bravin et al., Talk at LTD8, Dalfsen, Netherlands, August 15-20 1999

Figure captions

Figure 1: Shown is a summary of astronomical results for the mean matter density in the universe combined with a conservative estimate from primordial nucleosynthesis as a function of the Hubble constant. The dark dividing line titled Ω_B in the middle gives the allowed amount of baryonic matter in the universe (the lower band gives the amount of visible matter). The gap between Ω_B and the observed matter density on large scales (summarised as everything above $\Omega_0 = 0.3$) represents the non-baryonic dark matter motivation (from [2]).

Figure 2: Summary of existing and planned direct detection experiments, classified according to their ability to discriminate nuclear recoils. The numbers to the left indicate the applied background reduction technique which is given in the legend below. Note the variety of methods which gives a hint on the diverse experimental techniques and detector concepts involved in this fast evolving field of research.

Figure 3: Collection of spin-dependent cross section limits for several direct detection experiments as function of the WIMP-mass (from [26]). Note the improved limit below 5 GeV and the large distance of limits to expectations (for neutralinos) for this particular interaction channel.

Figure 4: Short summary of the most intriguing result from the DAMA NaI experiment (from [31]). Note that the upgrade to 250 kg has been approved.

Figure 5: Summary of current WIMP-nucleon cross section limits for spin-independent interactions from the CDMS collaboration [36]. The best limit for WIMP-masses above 40 GeV stem from the DAMA collaboration, below CDMS now tests the DAMA evidence contour. The combined Ge-diode limit is shown as dash-dotted line and dashed the UKDMC NaI result (limited by the unknown fast pulse shape component, see text).

Figure 6: Summary of the DRIFT experiment and schematic view of their TPC setup [43] (for details, see text).

Figure 7: Shown are the background expectations for GENIUS according to Monte-Carlo simulations [24]. Contributions from liquid nitrogen, the holder system, external background and cosmic activation have been included. Also shown is the sumspectrum and the contribution from the two-neutrino double beta decay of ^{76}Ge in the natural germanium crystals.

Figure 8: CRESST phase II setup and test measurement results [12] (for details, see text).

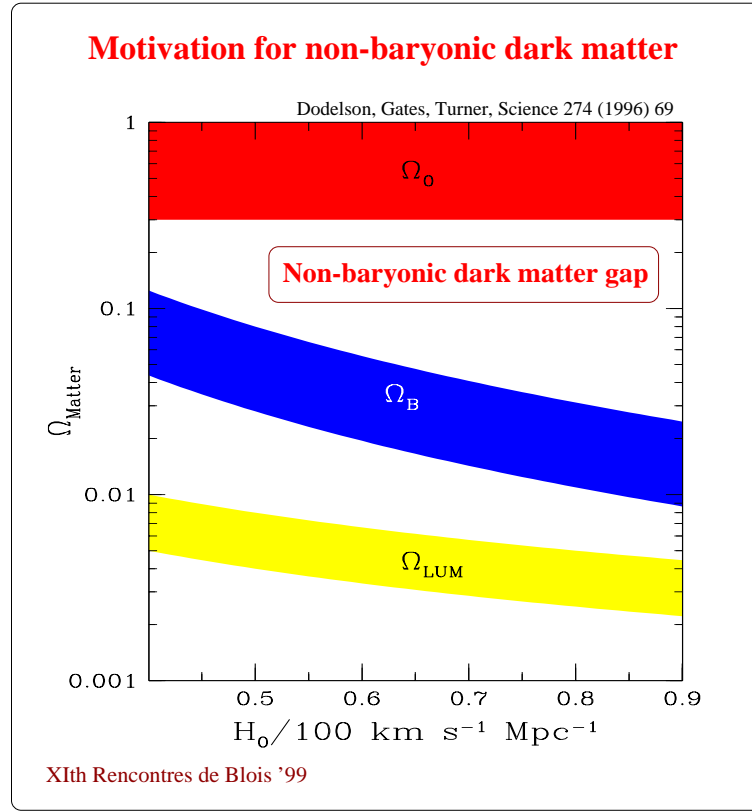


Figure 1:

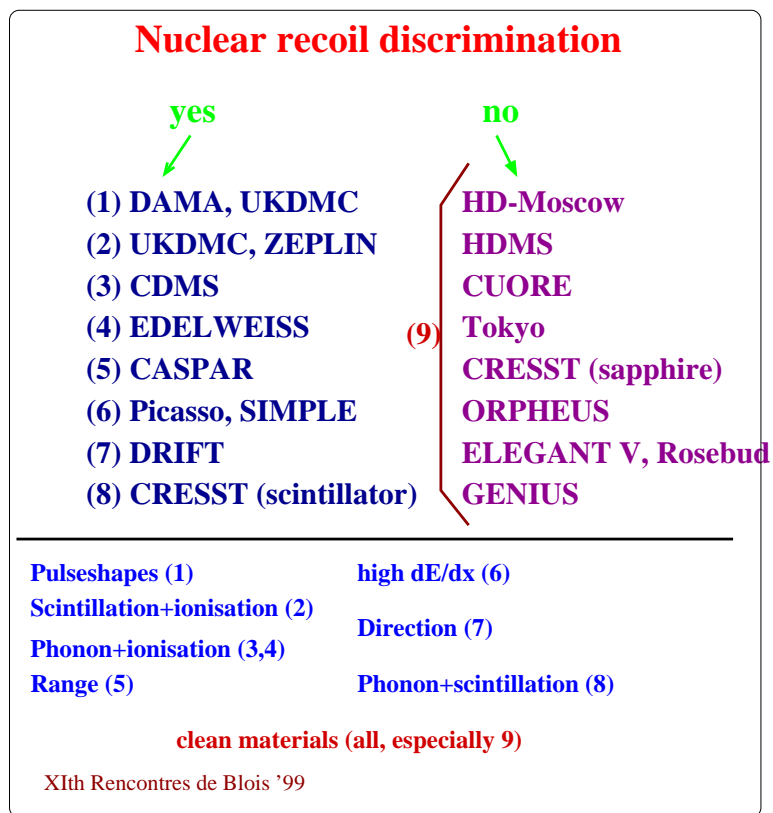
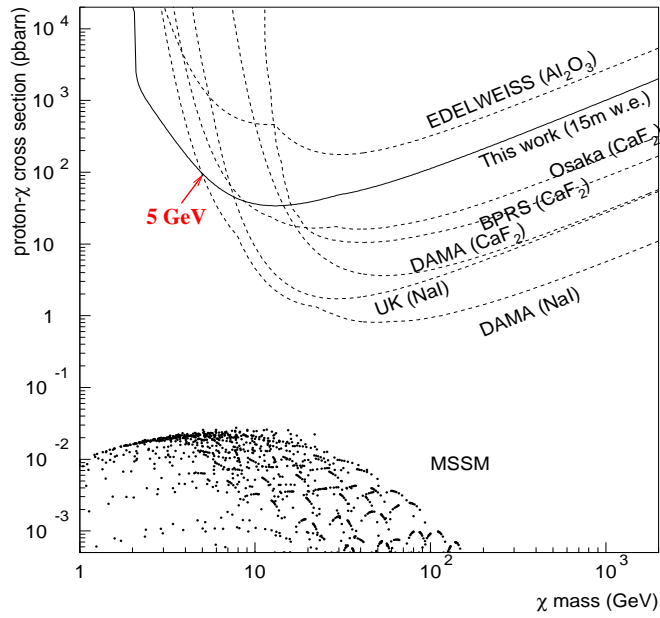


Figure 2:

Summary spin-dependent limits from Tokyo LiF

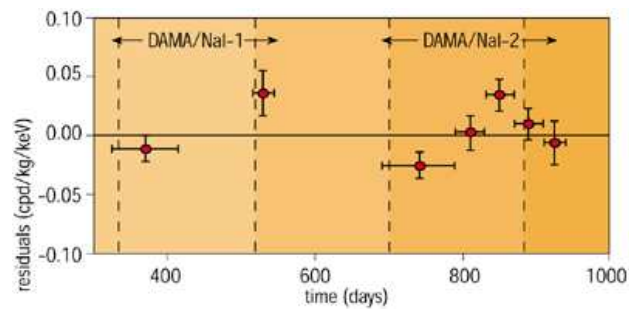


XIth Rencontres de Blois '99

Figure 3:

The DAMA NaI Experiment

- Analysed 19511 kg d over a 2y period
- Raw Data from 9 NaI-detectors, active mass: 87.3 kg
- Continuous stability control system -> control systematics
- Continuous data-taking and upgrade to 250 kg this year



XIth Rencontres de Blois '99

Figure 4:

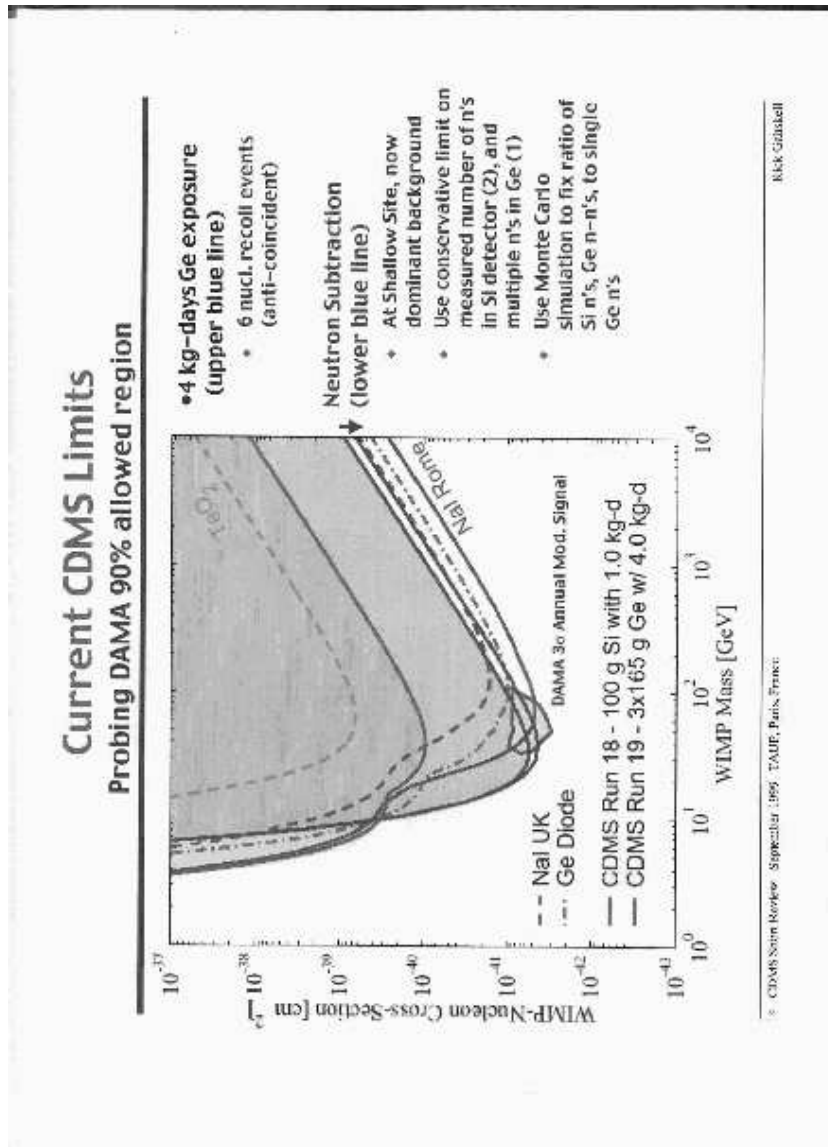
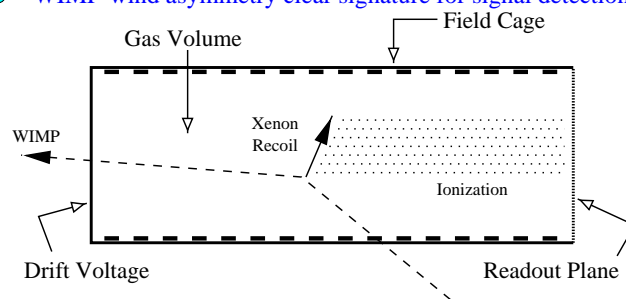


Figure 5:

The DRIFT Experiment

- low-pressure TPC, using 20 torr Xe-CS₂(50:50) gas mixture
- The only test-phase operating recoil-direction sensitive experiment
- WIMP-wind asymmetry clear signature for signal detection



- CS₂ negative ion drift -> no magnetic field needed
- 3D-track reconstruction possible; wanted < 1mm track resolution
- 20m³ active volume planned

XIth Rencontres de Blois '99

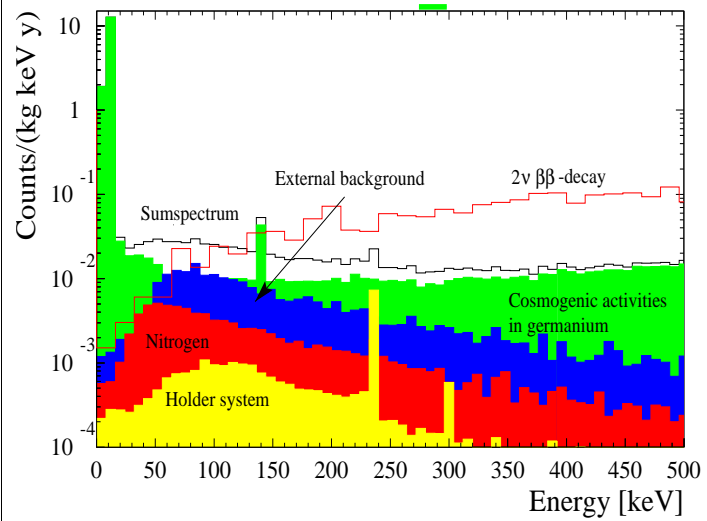
Figure 6:

The GENIUS Experiment

Monte-Carlo simulation of envisioned setup including all foreseeable background contributions.

Most dangerous: cosmogenic activities inside Ge-crystals

Estimated background: 3.1×10^2 c/y/kg/keV [<100 keV]



XIth Rencontres de Blois '99

Figure 7:

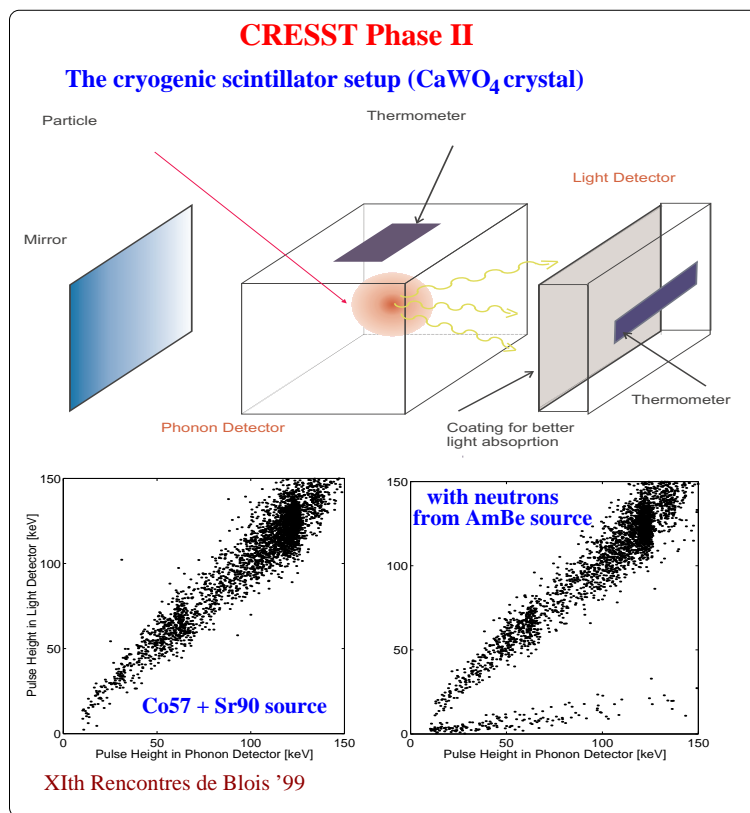


Figure 8: